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CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis

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ABSTRACT

Currently, the energy structure with coal is given priority to in China. This situation would not change in a short time which results in massive CO_2 emissions and increased pressure to natural environment. Carbon capture and storage technology (known as CCS) is a carbon abatement technology that separates CO_2 from industrial production or energy conversion, transports to the storage site after compression, and injects to the deep underground to make long-term isolation from the atmosphere. This technology achieves zero emission during fossil energy extraction and conversion, so the Intergovernmental Panel on Climate Change (IPCC) regarded it as one of the effective methods reducing greenhouse gas emissions in 2005. First, based on the development status of CCS in China, in terms of policies, technology research and CCS projects are described. SWOT is an analysis method that analyses objects all-around from four main aspects of strength, weakness, opportunity and threat. By SWOT, this paper focuses on analyzing the development environment currently in order to find the main stimulatives and obstacles and confirm the feasibility of CCS development in China. Finally, recommendations are proposed addressing the problems and obstacles. The results show that CCS is an effective way to reduce future emissions in China, as with the huge market, and the general support by Chinese government and green groups. However, relevant departments should strengthen economic and policy support at the same time.

Contents

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1. Introduction

With the development of global economy and the growth demand for fossil energy consumption, significant emissions of greenhouse gases, especially CO_2 (carbon dioxide), lead global temperature and sea level to rise continually [1]. Therefore, how to cope up with global climate change and control greenhouse gas emissions effectively are the dominant issues of the governments and the focus of the populace. CO_2 occupies most emissions produced by human activities, thus, CO_2 emissions reduction is an effective solution to solve the problem above [2,3]. As coal is the main energy source in China, CO_2 emissions caused by fossil fuel combustion account for more than half of total emissions, in which the emissions from the electric power industry and heat energy industry reach above 37% (as shown in Fig. 1) [4]. Therefore, study on how to reduce CO_2 emissions, especially in electric power and heat energy industry, has important practical significance.

Currently, developing renewable energy sources and improving energy conservation and emissions reduction technology are the mainstream methods for realizing emission reduction. Most renewable energy, including the wind energy and solar energy could be considered cleanly because of no directly carbon emissions during using process. Therefore, the positive development of renewable energy has significance to reduce carbon emissions and achieve reduction targets of China. According to statistics by National Energy Administration, while using renewable energy generates electricity instead of coal, each 1 kW h can reduce CO_2 emissions valuing 0.7–0.85 kg. During 11th Five-Year period (from 2006 to 2010), there are 2.5 billion tons emission reduction achieved by renewable energy power generation. And this data is expected to be 7.15 billion tons with generating totally 6 trillion kW h by renewable energy (hydro energy, wind energy, solar energy and biomass energy) during the 12th Five-Year (from 2011 to 2015) [5]. Although the effect of carbon reduction with renewable energy is obvious, there are certain difficulties throughout developing renewable energy to reduce emissions immediately: development of new energy resources such as solar energy, wind energy and biomass is always restricted by technology and environmental conditions as well as low efficiency and high cost; while the scale of hydropower is limited by environmental conditions and safety issues [6].

In contrast, there are larger development space and fewer restrictions of energy conservation and emissions reduction technology, which make the technology to be more feasible approach. Currently, emissions reduction technologies advocated in China include contract energy management, electric vehicles, CCS technology and so on. Different technologies have their own characteristics and advantages. Contract energy management has efficiency in energy conservation and emissions reduction. With the highest efficiency of contract energy management reaching 40–50% in China, 45.71 million tons of carbon emission reduced in 2012 by energy service companies (ESCOs). However, in the case of imperfect law system, credit risk threatens ESCOs. ESCOs bear the most risk resulting in low enthusiasm and the limited development space in future. While electric vehicle (EV) control CO_2 emissions from the terminal end, but the using energy is

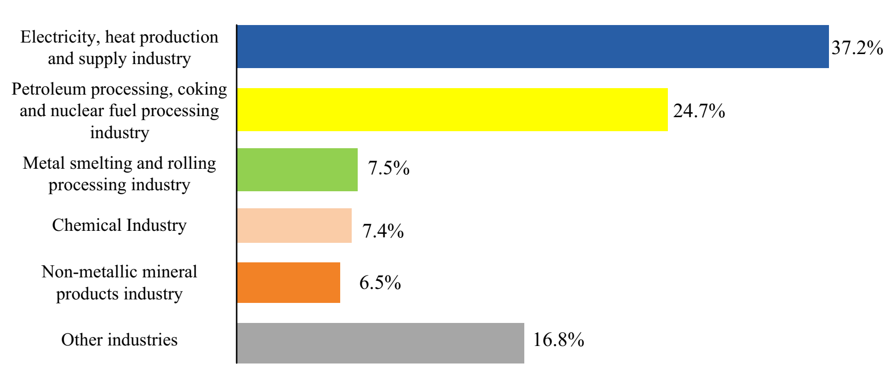

Fig. 1. CO_2emission source scale drawing in 2011.

transformed from fossil fuels mainly. Thus, seen from industry chain, the emissions caused by EV is still vast. With the addition of the restrictions of capital and technology, EV faces huge obstacles in popularization. By contrast, programs of CCS technology contain no complex business relationship, and the technology can achieve zero-emission in the whole process of fossil energy extraction, conversion and usage. Emission reduction is thorougher. To be specific, CCS is the technology that separates CO_2 from industrial production or energy conversion, transports to the storage site after compression, and injects to the deep underground to realize zero emissions in the process of fossil energy extraction, conversion and usage. China has more than 2500 coal seam wells and extensive deep saline aquifers, storage potential can fully meet the storage requirements, as shown in Table 1 [7]. In addition, the enhanced oil recovery technology and Enhanced Coal Bed Methane technology (known as EOR and ECBM) can improve oil and gas exploitation effectively [8]. Thus, CCS technology has strategic significance for emission reduction and low-carbon economy of China [9].

At present, carbon emissions in China reach 10 billion tons each year. CCS technology mainly applies in large industrial fixed emission point of electricity industry, chemicals industry, cement industry and so on. The required size of carbon capture and storage in Table 1 is the theoretical value deduced by the carbon emissions and capturing rate. In fact, without realizing large scale and commercialization, the real size of carbon capture and storage in China currently does not have a precise statistic. After summarizing major domestic CCS projects in Table 2, the real size of carbon capture and storage is inferred about 300–350 thousand tons. Calculated by Shenzhen Stock Exchange's emissions carbon price of 83 yuan per ton (April 18, 2014), the direct economic

Table 1
Required size of carbon capture and storage in China.
Source: Ref. [10].

	Value
Capture size	25–35(10^8 t/year)
Storage size	25.7–33.5(10^8 t/year)
Storage potential	2300(10^9 t)

Table 2
Main CCS projects and size in China.

Project/enterprise	Carbon capture and storage capacity
China Jilin Oilfield	20×10^3 t/year
Huaneng Beijing Thermal Power Plant	3×10^3 t/year
Huaneng Shanghai Shidongkou Second Power Plant	120×10^3 t/year
CPI Shuanghuai plant in Chongqing	10×10^3 t/year
China Shenhua Inner Mongolia project	100×10^3 t/year
CPI Hechuan Plant	10×10^3 t/year

Table 3
Relevant laws and regulations.
Source: Ref. [18].

Time	Name	Content
1989	Environmental protection law	Stipulate that planning about construction and development and utilization, special planning and construction projects shall be conducted environmental impact assessment in accordance with the law, and further stress the legal effect of environmental impact assessment documents, which guarantees carbon sequestration project's impact on the environment for scientific evaluation
2000 (latest revision)	Atmospheric pollution prevention law	The law is prompted to make the CO_2 including, on control of CO_2 emissions
2003	Environmental impact assessment law (Interim measures on public participation in EIA and Planning environmental impact assessment ordinance)	Provisions for supervision basis of problems as public supervision and punishment not in conformity with the specified project in CCS implementation process
2002 (approved)	Kyoto Protocol	Points out that CCS is effective measure to stabilize CO_2 concentration, flexible response to reduce greenhouse gas emissions
2006.2.9	Long-term Scientific and Technological Development Plan (2006–2020)	Puts "develop efficient, clean and nearly zero CO_2 emissions development and utilization technology of fossil energy" included in the category of advanced energy technologies
2007 (latest revision)	Law of energy	Encourage the use of CO_2 flooding purging
2007.6.4	China's national plan to address climate change	Proposes "Efforts to develop CO_2 capture, utilization, and storage technology"
2007.6.14	Science and technology special action to address climate change in China	"CO_2 capture, utilization and storage technology" is included into the key tasks
2008.10.29	Policy and action of China's response to climate change ", white paper	Points out that "China has determined to focus on the research of CO_2 capture, utilization and storage technology"
2009.5.25	The state environmental protection technology evaluation and demonstration administration measures	Provides reference in view of pollution prevention and control technology such as ecological restoration, cleaner production and circular economy, as CCS evaluation
2010.5	Guide for carbon capture and storage	The most comprehensive CCS guidelines, expected to promote in the whole world, and provide support for the industry and regulators. The breakthrough significance lies in acceleration of large-scale deployment of CCS projects
2011.7	The national "12th five-year" science and technology development planning	Proposes develop CO_2 capture and storage technology, creates well policy environment for CCS development
2012.7	The national "12th five-year" science and technology development planning to address climate change	Points out that "study biological carbon sequestration project technology and greenhouse gas emissions reduction technology through change of land use and regulation of agricultural production, to carry out the CO_2 capture, utilization and storage technology research and demonstration"
2013.2.16	The "12th five-year" national carbon capture use and storage technology development special planning	Effective implements cooperating with the state council 12th five-year control scheme for greenhouse gas emissions, to overall coordination and comprehensively promote the CO_2 capture, utilization and storage technology research and demonstration

benefits of the real size can reach 24.9–29.05 million each year currently without including the economic benefits gained by the industry usage of carbon dioxide. With the potential excavated gradually, CCS technology can create benefits over 10 billion theoretically through the carbon market.

After studying the CCS status quo in China from the aspects of policies and regulations, technology researches and demonstration projects, the opportunities and challenges in the field of policy, technology, economy and environmental development are analyzed in this paper [11]. On this basis, comprehensive and systematic CCS development strategy that fits Chinese status is proposed, for reference.

The layout of the paper is as follows. Section 2 reviews on current situation of CCS from four aspects of the policies and regulations, technology research and development, domestic major demonstration projects and international cooperation. Section 3 the strength, weakness, opportunity and threat of developing CCS in China are analyzed to find the main stimulatives and obstacles with SWOT from following aspects: CCS storage conditions, storage capacity of coal seam, gas CO_2 storage capacity, geologic storage conditions, cost, energy consumption and technical. Section 4 puts forward related suggestions to promote the development of CCS technology in China. Finally, the conclusion is given in Section 5.

2. Present situation of CCS development in China

In view of the CCS development in China still infant, all aspects of progress are not clear enough, as well as the policy environment. In this part, research is launched in the following four aspects: the existing legal environment, development status of various technical taches of CCS, domestic CCS projects and international cooperation. On this basis, the policy environment, technical environment, internal and external market context currently are elaborate. Then, we clarify institutional, economic, technological and international environment of CCS development in China, in order to lay the foundation for subsequent further analysis.

2.1. Present situation of policy and regulations

2.1.1. Environmental protection law

The environmental protection law is the "basic law" in the field of environmental protection, with strategic guiding role in China. Environmental protection law proposes environment protection work must adhere to rely on scientific and technological innovation, law and system improvement, the principle of ecological safety, consistent with the original intention of CCS; Simultaneously clarifies CCS shall abide the principle of protecting human health and ensure for ecological security, to avoid leakage accident and other abnormal accident. Environmental protection law article 13 modified draft did bridging with the current law regulation: the provisions on the construction and development and utilization planning, special planning and construction project shall be conducted environmental impact assessment according to the law, and further define the force of law of the environmental impact assessment documents, protecting scientific evaluation on the impact of carbon storage project implementation before and after on the environment, reducing the occurrence of destroy [12].

2.1.2. Atmospheric pollution prevention law

No regulation for CO_2 is involved in the atmospheric pollution prevention law currently. CO_2 is not regarded as "pollution" with reference to the definition of "water pollution" in the law. In 2007 the state council formulated the national plan to address climate change and the notice on comprehensive energy saving and emission reduction work plan, set up a leading group for energy conservation and emissions reduction work under the state council in addition [13], through the ways to launch energy conservation and emissions reduction actively, rather than the law of emission reduction obligations. Atmospheric pollution prevention law can be considered to expand to the law "affect atmospheric environmental material", including CO_2 in the law, to regulate CO_2 emissions in legal aspects.

2.1.3. Environmental impact assessment law

The environmental impact assessment law at present in China still is not perfected. Interim measures on public participation in EIA and the planning environmental impact assessment ordinance established make up for the part of the defects of environmental impact assessment law, but the problems such as public supervision, ineffective punish violations are still not well resolved [14,15]. In terms of public participation, information disclosure ways of environmental impact assessment agency that construction project units themselves or they authorized are some single, limiting the public participation, and resulting in the lagging of public participation in time. For that CCS projects have the characteristic of high risk, it is not easy to obtain public support, public information is particularly important in a timely and effective manner. In addition, the "not approved building" problems exist hidden dangers, and penalty is far from enough. The law of EIA article 24 points two hundred thousand as the upper limit of penalty, while long construction cycle, big intensity and high cost of CCS projects, the penalty is not enough for the CCS capture and storage projects not conform to the standard and process.

2.1.4. Law of energy

The law named as "energy" associated with CCS at present in China is energy conservation law, "energy-saving technical progress" in the law of the fourth chapter can be regarded as legal basis of the encouragement to use CO_2 flooding gas [16]. But the rules are too indirect to explicitly support for carbon capture and storage project. Britain in 2010 promulgated the energy law, adapting to the UK low carbon transition plan in 2009, from the aspect of law clarified support for CCS development: necessary financial support for CCS, four commercial CCS demonstration projects in the construction, report on the progress of UK CCS project on a regular basis [17]. Comprehensive energy law, by contrast, has not launched yet, the new "energy law" is still in legislation, and the energy is still in the single law norms as the main basis (as shown in Table 3).

2.2. Present situation of technology development

CCS technology captures CO_2 of energy industry and other industries production, with the utilization of mature technologies such as adsorption, absorption, low temperature and membrane system, and storages CO_2 for long-term or permanent. The whole process includes the capture, transportation and storage [19,20] three stages, Fig. 2 shows the main process:

2.2.1. CO_2 capture technology

CO_2 capture technology separates CO_2 from industrial production by a certain method, so as for storage and use [21,22]. The capture object mainly focuses on large-scale CO_2 concentration emission source, such as coal-fired power plants. CO_2 capture technology can be divided into the post-combustion capture, pre-combustion capture and oxygen-enriched combustion capture at present [19,20]. The principle, advantages, disadvantages, appliance

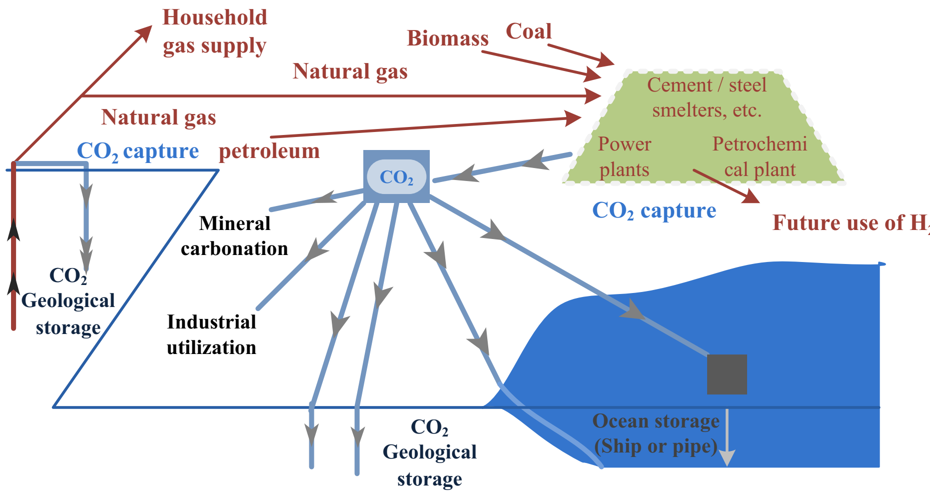

Fig. 2. CCS flow diagram.

object and technical maturity of three technologies are different (as shown in Table 4).

2.2.2. CO_2 transportation technology

CO_2 transportation technology refers to various methods transport CO_2 after separated and compressed to store place safely [25]. Commercial scale transportation modes are pipeline, truck and shipping transportation (as shown in Table 5) [19,20]. The pipeline has the largest application advantages, is divided into two types: the land pipeline and offshore pipeline. CO_2 pipeline practice abroad has more than 40 years experience, and the main pipeline length of the United States operating is more than 5000 km. In China, the transportation is given priority to with land low temperature storage tank, still no business of CO_2 pipelines. Compared with abroad, the main technological gap lies in planning and optimization design technology of CO_2 source matching network, pipeline key equipment such as large displacement compressor, and safety control and monitoring technology, etc. Truck stores CO_2 in the form of liquid in the car cryogenic liquid tank insulation on-board. Storage conditions for storage tank are temperature is from -20 °C to 30 °C, the pressure 1.5 MPa to 2.5 MPa, not suitable for large scale CCS project due to technical difficulty. Shipping is similar to truck, for long distance the transportation has advantages for sea storage site.

2.2.3. CO_2 storage technology

CO_2 storage technology refers to a variety of technical measures and methods realizing CO_2 arrival of stored underground injected into saline aquifers, depleted oil and gas fields, coal mines and other geological structure layer or deep seabed, seabed geological formations, including ocean storage, geological storage, ore carbonation and industrial utilization (as shown in Table 6) [16,17]. Ocean storage and geological storage are widely used and relatively effective. Three types of geological structure can be used for CO_2 geologic storage: deep saline aquifers structure (DSR), Enhanced Oil Recovery, EOR [26] and Enhanced Coal Bed Methane, ECBM. Major technology gap, compared with abroad, behaviors reservoir engineering design, technology, key equipment, etc in the use of CO_2 drilling for oil in China.

2.3. Demonstration projects in China

The energy industry becomes the main fields of CCS demonstration projects in China due to large amount, fixation, and concentration of CO_2 source (as shown in Table 7). In July 2008, CO_2 capture demonstration project of HUANENG Beijing thermal power plant officially was put into operation, marked the CCS technology has been applied in the electric field for the first time in China. The project plans to collect and use the waste gas in generation, CO_2 recovery designed greater than 85%, recovery CO_2 capacity 3000 t, CO_2 purity after separation and purification above 99.5%.

HUANENG Shanghai Shidongkou II thermal power plant CO_2 capture project (2009), China Power Investment Co., LTD. Chongqing Hechuanshaunghuai power plant CO_2 capture project (2010) have been put into operation after Beijing thermal power plant, capture capacity designed are 100,000 t and 10,000 t, respectively. AS coal chemical industry is one of the important potential CCS demonstration projects areas, because of numerous coal chemical industry enterprises in China, as well as high concentrations of CO_2 and low capture energy consumption, therefore, the coal chemical industry have great potential for CCS application.

The first global whole process of CCS projects storing CO_2 in salty water layer-SHENHUA CCS industrialization demonstration project started in June 2010. SHENHUA CCS demonstration project has been on successfully injected supercritical CO_2 into the target layer on January 2, 2011, marked SHENHUA CCS demonstration project test succeeded. After the final completion homework, the project started formally continuous injection, and completed the production test, and obtained first-hand data on May 2011. The second continuous injection began on September 16, 2011 after maintenance and installation process optimization. In August, moreover, "Guang Dong CO_2 Capture and Storage Research" (GDCCSR) project investigation group, observed SHENHUA CCS demonstration projects in Northeastern Ordos Basin. The injection is ideal, underground parameters are smooth, and data collection is complete currently.

SHENHUA CCS projects achieve important results in operation practice: forming the continuous perfect CO_2 injection scheme through the optimal control methods; determination of CO_2 injection temperature, pressure, flow rate and other important parameters using numerical simulation, engineering analogy and theory analysis method; obtaining the complete formation pressure coefficient, effective permeability of reservoir, production capacity and other stratigraphic formations characteristic parameters through the interference test; establishing CCS process, monitoring database operation system and the target area geology model; grasping the dynamic reservoir geological evaluation analysis method. SHENHUA CCS demonstration projects of 100,000 t/year completed and were put into operation for more than a year on August 6, 2012, having been storing CO_2 4 million

Table 4
CO_2 capture technology.
Source: Ref. [23,24].

Technology	Principle	Advantages	Disadvantage	Applicability	Technical maturity	
					International	Domestic
Post combustion	Separation device is installed on the flue gas channel of combustion equipment (boiler or gas turbine), captures CO_2	Relatively mature technology, and better matching with existing plants, suitable for the reconstruction of old power plants	High capture energy consumption, generation inefficiency, and higher transformation investment cost	Traditional PC power plant	Feasible under Specific conditions	Research/ Small-scale Demonstration
Pre combustion	Gasification of coal hyperbaric oxygen to gas, again after water–gas transformation produces CO_2 and hydrogen	Mature separation process; separation equipment is small in size; smaller and more efficient	Matches with IGCC plants only, higher investment costs	New IGCC plant	Feasible under Specific conditions	Research
Oxy-fuel	N_2 removal by oxygen in high proportion, mixed gas of high concentration of oxygen and withdraw part of the flue gas instead of air	directly processed and archived, simple procedures	High heat resistance of boiler materials, and energy consumption oxygen purification, more costly	Conventional pulverized coal power plants	Demonstration	Research

Note: PC—pulverized coal.
IGCC—integrated gasification combined cycle.

Table 5
Means of CO_2 transportation technology.

Technology	Advantages	Disadvantage	Technical maturity	
			International	Domestic
Pipeline transportation	Large transport capacity, and long distance	Transportation costs greatly influenced by the geographical conditions	Mature	Research
Truck transportation	Flexible and adaptable	Leakage evaporation risk exists (maximum evaporation capacity of up to 10% of traffic), high transport costs and small amount	Mature	Mature
Shipping transportation	Large transport capacity, suitable for long-distance	Short distance, uneconomic(<1500 km)	Feasible under Specific conditions	Research

Table 6
Carbon storage technology.
Source: Ref. [27,28,29].

Program	Strengths	Weaknesses	Cost($/t)	Potential (10^9 t)		Technology maturity	
				Global	Domestic	International	Domestic
Ocean storage	Large reserves, permanently sealed CO_2	PH value and pH change, ecological damage	–	–	–	Simulation demonstration	Research
Depleted gas field	Storage in good condition; infrastructure facilities; experienced storage	Large depleted gas field required	1.2–19.43	675–900	4.1–30.5	Feasible under Specific conditions	Research
EOR	A certain economic and commercial value; relatively mature technology	Relatively high demands on the reservoir; low storage capacity	−91.26–73.84		4.8–10.1	Mature	Feasible under Specific conditions
ECBM	Increase CBM; certain economic and commercial value	Poor Closed; immature technology	−25.72–18.88	15–200	12.1–48.4	Demonstration	Research
Deep saline aquifers	Storage potential; widely distributed	Uncertain sealing groundwater resources pollution	1.14–11.71	1,000–10,000	160–1451	Feasible under Specific conditions	Research
Ore carbonation	Ion carbonate stable Formatted	Slow natural reaction, high energy consumption	–	–	–	Research	Research
Industrial utilization	Re-use resources, more economical	Small industrial utilization potential; only kept for a short period (months to years)	–	–	–	Research	Research

tons accumulatively, obtained the breakthrough in the field of CCS demonstration projects [30].

"Carbon capture and storage research of gas power plant" sponsored by DATANG International Power Generation Co., Ltd. and the Asian Development Bank was launched on August 15, 2012. On December 12, 2012, HYANENG Tianjin IGCC demonstration plant was put into production. The Asian development bank technical assistance project, "Demonstration and application of road map of CO_2 capture and storage technology" started up on December 14, 2012. Carbon capture process of coal-fired and gas-fired power plant in China is accelerated increasingly.

2.4. International cooperation

International cooperation CCS projects between China and other countries or organizations recently carry out with the rapid

Table 7
CCS projects of large-scale power plants in China.
Source: Ref. [31].

Business	Start/production time	Project description
Jilin Oilfield	2006 (start)	Efficient CO_2 capture, storage and oil safety tests, CO_2 had been injected 7 million t to 2009.9, predicted EOR 14% increased
HUANENG Beijing Thermal Power Plant	2008.7 (production)	First coal-fired power plant combustion CO_2 capture demonstration project in China', CO_2 capture capacity reached 3000 t/Year
HUANENG Shanghai Shidongkou II Power Plant	2009.12 (production)	The world's largest post-combustion CO_2 capture demonstration project currently, capture and purify 120,000 t/year, the cost is only 30% of the United States similar projects
HUANENG Tianjin IGCC demonstration power plant	2009 (start)	IGCC system, is the world's most environmental-friendly efficient power generation and low-emission coal-fired power generation technology currently, the first phase of 250 MW was built by the year 2011
CPI Chongqing Shuanghuai plant	2010 (production)	Post-combustion capture device, independent technology, capture and purification of 10,000 t/year
HUANENG group	2010.6(start)	First full process of CCS demonstration projects in China, including capture and saline aquifer injection storage. The storage capacity is 100,000 t/year. The project will be completed in two steps of capture and storage of 1 million t and 3 million t

increase. China-EU Cooperation on Near Zero Emissions Coal-NZEC is one or the important cooperation projects in the field of climate change, especially the CCS area between China-EU [32]. China-EU NZEC project is conducted in three phases: first phase is pre-feasibility study on ability construction and demonstration projects, second phase is feasibility study on demonstration projects, third phase is to construct and operate CCS demonstration projects in China. The first phase of the project had been started in November 2007, ended in the autumn of 2009. The second stage substantive cooperation is under active discussion and study.

COACH (CO_2 Operation Action within CCS China-EU) has confirmed two sets of demonstration schemes with the utilization of integrated gasification combined cycle and pre-combustion CO_2 capture in China since the agreement was signed in 2005 [32]. The project confirms an increase of the storage capacity of 500 million tons of CO_2 in SHENGLI oil field and DAGANG oilfield, 23 million to 112 million tons of oil production increase estimated. Support to Regulatory Activities for CO_2 Capture and Storage-STRACO2 emphasizes laws and regulations have been established by EU can be references for relevant legislation systems in China, namely the "two-step method", first agreement for carbon capture and storage demonstration plants a looser legal framework, providing sufficient flexibility; And then determination with a more comprehensive regulations on the basis of demonstration projects experience [32].

HUANENG-CSIRO post-combustion capture demonstration projects were constructed by Australia's Commonwealth Scientific and Industrial Research Organization-CSIRO, China HUANENG Group Company and XI'AN Thermal Power Research Institute-TPRI jointly. The project is designed for carbon capture retrofit of HUANENG Beijing Gaobeidian thermal power plant, reach CO_2 recovery greater than 85%, recovery of CO_2 capacity of 3000 t. The demonstration project had been formally put into production on July 16, 2008.

These projects related to CCS development policy, capture technology, storage assessment, and other fields, provide support of capital, technology, etc for CCS development in China.

All in all, study above finds that policies and regulations relevant to China's CCS technology and projects carried out are increasingly clear and focused, but the technical conditions are relatively immature. Moreover, domestic CCS projects have attracted less attention compared to previous years, and the international cooperation activity has also been inadequate. In view of this, the deep-seated causes of the situations should be analyzed intensively, in order to give specific recommendations and measures to promote the rapid development of CCS technology in China, which is the major work in the next sections.

3. SWOT analyses on CCS development in China

The previous analysis demonstrated that the situation of China's CO_2 emissions is quite grim, and CCS technology in China has a certain foundation for further development, so it is considered an effective measure to solve the carbon emissions. However, the internal and external environment for further development and the conditions to carry out large-scale CCS projects are not very clear. Therefore, the strategic analysis of SWOT (constituted by the initials of strength, weakness, opportunity and threat) is applied to study the advantages, weaknesses, opportunities and potential obstacles of China's large-scale development of CCS, achieve to identify development environment of CCS technology in China, and analyze the causes of the existing deficiencies and obstacles, in order to put forward suggestions to promote the development.

3.1. Strength of CCS development in China

3.1.1. Great government support

China has always attached great importance to climate change and greenhouse gas emissions, to promote the development of CCS in China, files and programs support to promote energy conservation and emissions reduction have begun issued since 2008 [33]. As shown in Table 8.

3.1.2. Coal-dominated energy structure

Demand for electricity and power capacity is increasing with the rapid development of domestic economy. Subject to China's energy structure, though clean energy (hydropower, wind power, nuclear power) is in good momentum of development, the thermal power installed capacity still maintains growing (as shown in Table 9 and Fig. 3). Above coal-dominated energy structure externalities have negative impact on the environment apparently. With the increasing environmental pressure, in order to complete the target while guaranteeing the power supply, to promote the widespread implementation of CCS in China, within developing clean coal technology and improving the efficiency of power generation, promoting the overall goal of energy conservation and emissions reduction.

3.1.3. Huge geologic storage potential

Geologic storage grows fast aboard, geologic storage sites can be used include: oil and gas reservoirs, deep saline aquifers and deep un mined-coal seams. Major large-scale basin sediments multi-layered depositional systems, affected by the new tectonic movement, sealing conditions are better. The large land basins of China mostly have been tested (underground storage) CO_2 flooding test, a target zone of CO_2 underground storage perhaps. The geological cognition degree of these basins is well, land deep saline formations, oil and gas fields, mining fields cannot are good underground space for CO_2 geological storage. CO_2 concentration emission source in China are mainly distributed in the eastern region of China, a significant proportion located in the sedimentary basin, in short distance from the potential geologic sequestration sites (especially deep saline layer) (as shown in Fig. 4) [36], implies CCS implementation if so can greatly reduce the transportation cost. Coal seam storage in geologic sequestration can effectively reduce CO_2 emissions, increase CBM production can be mined, reduce the cost of CO_2 stored underground. According to coal and coal bed methane exploration data in China, mining coal-bed methane technology using CO_2 injection can store about 1.2078 billion tons CO_2; while underground natural gas storage projects are already built infrastructures such as pipelines and drilling, greatly reducing CO_2 storage cost [37].

3.2. Weakness of CCS development in China

3.2.1. Poor economic feasibility

CO_2 capture cost is high, accounting for 70–90% of the total cost of the whole CCS progress. Research shows that, the application of CCS will make coal-fired power generation efficiency loss 20–30% for a coal-fired power plant, therefore implementation of CCS compared to without CCS consumes about 25% more of the coal to produce the same amount of electricity, the corresponding cost will be increased by 40–80%. In addition, the increase coal consumption cost will spread to the whole energy system through the coal industry chain, coupled with the external cost of coal production and transportation link (e.g., impact of environment, safety, and ecological), the cost will greatly increase [38].

Among CO_2 capture presently, oxy-fuel capture is still in the development stage, post-combustion and pre-combustion capture technology is feasible. Post-combustion capture fits for traditional PC power plant, according to IPCC estimates, the capture cost is about 29–51$/t; pre-combustion capture primarily for new type of IGCC power plant, cost is about 13–37 $/t. In addition, involved in the upfront install costs of CCS equipments, CO_2 capture cost will be higher, due to no installation of CCS related devices in traditional coal power plants in China. CO_2 concentration is higher, capture cost is relatively low of IGCC, although, IGCC system is complex, initial investment is extremely high, the fixed investment as much as 1430$/kW, while fixed investment of traditional supercritical pulverized coal power plant reaches about 1330$/kW [39]. The investment cost is $50 million difference with an installed capacity of 500 MW power plant as an example. CO_2 pipeline transportation cost should be considered in transportation and storage period, including pipeline engineering investment and operation and maintenance costs. CO_2 emissions of

Table 9
Thermal power installed capacity in China.
Source: Ref. [35].

Year	Total installed capacity(100 million kW)	Thermal power installed capacity(100 million kW)	Thermal power proportion (%)	Thermal power (100 million kW h)	Growth rate (thermal power installed capacity)
2005	5.1	3.82	74.9	21,032	/
2006	6.22	4.84	77.8	23,162	0.2670157
2007	7.13	5.54	77.7	27,012	0.1446281
2008	7.92	6.01	75.87	27,857	0.0848375
2009	8.74	6.52	74.6	29,814	0.0848586
2010	9.62	7.07	73.4	32,958	0.0843558
2011	10.63	7.68	72.25	38,137	0.0862801
2012	11.45	8.19	71.55	37,867	0.0664063

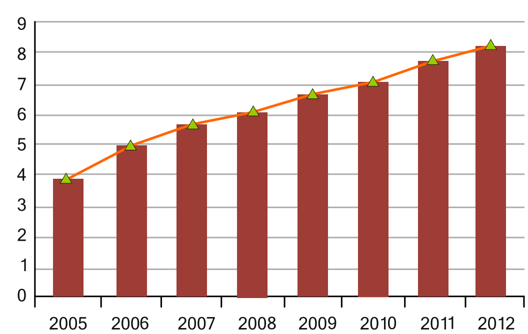

Fig. 3. Thermal power installed capacity change trend in China (unit: 10^8 kW). *Source*: Ref. [35].

Table 8
Policies and documents promoting CCS energy conservation and emissions reduction nearly five years.

Time	Policy/meeting	Content
2008.10.29	Policy and action of China's response to climate change ", white paper	Points out that "China has determined to focus on the research of CO_2 capture, utilization and storage technology"[34]
2009.5.25	The state environmental protection technology evaluation and demonstration administration measures	Provides reference in view of pollution prevention and control technology such as ecological restoration, cleaner production and circular economy, as CCS evaluation
2009.11.25	State Council executive meeting	Per unit of GDP of China emission is estimate decreased by 40–45% from 2005 to 2020, as binding targets involved in national economic and social development long-term planning. And developing appropriate national statistics, monitoring and evaluation methods
2010.5	Guide for carbon capture and storage	The most comprehensive CCS guidelines, expected to promote in the whole world, and provide support for the industry and regulators. The breakthrough significance lies in acceleration of large-scale deployment of CCS projects
2011.7	The national "12th five-year" science and technology development planning	Proposes develop CO_2 capture and storage technology, creates well policy environment for CCS development
2012.7	The national "12th five-year" science and technology development planning to address climate change	Points out that "study biological carbon sequestration project technology and greenhouse gas emissions reduction technology through change of land use and regulation of agricultural production, to carry out the CO_2 capture, utilization and storage technology research and demonstration"
2013.2.16	The "12th five-year" national carbon capture use and storage technology development special planning	Effective implements cooperating with the state council 12th five-year control scheme for greenhouse gas emissions, to overall coordination and comprehensively promote the CO_2 capture, utilization and storage technology research and demonstration

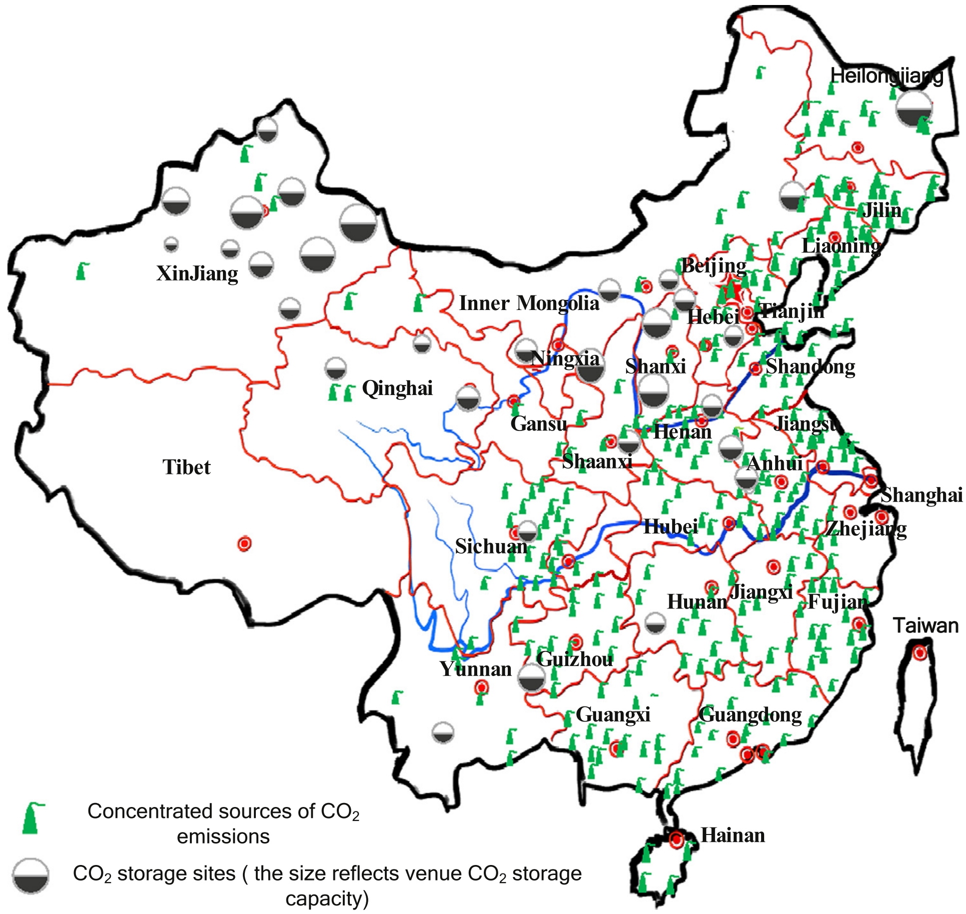

Fig. 4. Principal sources of CO_2 emissions concentration and storage distribution in China.

production process if applying CO_2 enhanced oil recovery, include CO_2 leak aging into the atmosphere and indirect CO_2 emissions of equipment work, the economy remains to be measured [40].

3.2.2. Lack of capital source

With coal prices rising sharply and marketization gradually in China, electricity price still belongs to the typical "market coal and electricity plans", coordinated by the state planning, means that the plant can't pass the increased costs by coal price increased to consumers by means of raising electricity price simply. For the increased installation cost and over consumption cost of the coal of large-scale implementation of CCS, it is hard to pass to customers through electricity price adjustment.

Clean development mechanism-CDM, is one of three kinds of flexible implementation mechanisms Kyoto protocol set, the core is developed countries buy certified emission reduction (CER) from developing countries in the project cooperation way, on the one hand to ensure that developed countries can perform their part of the emissions reduction obligations, on the other hand, to provide money and technology to developing countries, promoting the sustainable development of developing countries. However CCS does not belong to the CDM projects at present, due to project boundary issues, persistent problem, leakage issues and sustainable development issues. Overall it is difficult for CCS in China to finance through CDM in the international category for financial support.

The international energy agency-IEA predicts that there will be more than 100 large CCS carbon storage projects intending to be carried out before 2020, the total cost is more than \$56 billion; \$600 billion is required in 2021–2030; In addition, most CCS projects in China can only achieve funds through the national science and technology plan, the central enterprise oneself, or with a small amount of international cooperation project funding support, due to imperfect incentive policy, uncertain business prospects. Lack of funds source and small volume, cannot meet the needs of rapid CCS development.

3.2.3. Immature technology

CCS is in the stage of research and demonstration basically, still a relatively new research field, suffering from the risk.

It is difficult to determine which kind of the future CCS capture technology on a large scale operation in China, due to the immature capture technology, and the applicable range, energy consumption and cost, etc have advantages and disadvantages. CCS transportation relies mainly on highway truck, rail tanker, pipes and shipping technology needed to be developed. Yet not comprehensive geological investigation in CCS storage, with no clear storage potential evaluation and site selection criteria, site survey technology and safety monitoring technology is lack.

In addition, the reliability of storage technology is highly controversial. CO_2 must rely on the formation pressure, maintained in a supercritical state, or it will evaporate into the air. So while so many places suitable for storage the global explored out, truly achieved storage sites are rarely, because of threat of leaks. Worry about the safety of CCS has been proposed publicly by multinational representatives at the Copenhagen climate conference. Related researches for the adsorption and migration mechanism after CO_2 injected into underground geological structure, chemical corrosion mechanism and laws on long distance pipeline CO_2 transportation, behavior change and regularity of CO_2

in the formation, chemical reaction and curing conditions and so on have just started. Currently the storage volume of CCS demonstration projects under running, argumentation, and construction and sequestration is still low, and small compared to the large-scale billions of tons of storage CCS promotion needs, which is difficult to demonstrate long-term security and stability of the implementation of CCS on a large scale.

3.3. Opportunities of CCS development in China

3.3.1. Increasing environmental pressure

Greenhouse gas emissions reduction to slow climate change becomes the hot topic of international society. China faces dual pressure of more and more demands from the international community to undertake the obligation to reduce greenhouse gas emissions and domestic resources and environment sustainable development [41]. The increasing environmental pressure will supervise and urge the government to reduce CO_2 emissions, promote the resources recycling, and improve government and the public's awareness of environment. Thus the widespread implementation of CCS technology in China, with CO_2 utilization and storage, will reduce carbon emissions, promote industrial utilization of CO_2, and realize climate change mitigation and environmental protection. According to statistics by National Energy Administration, theoretical emission reduction of CCS technology in China is up to 2.5–3.5 billion tons per year, equivalent to 26–37% of Chinese annual emissions. The annual emission reduction of SHENHUA Group CCS demonstration projects is equivalent to the amount of carbon dioxide absorbed by 280 ha of forest. The amazing potential reduction has significant importance to alleviate the current growing pressure of environmental protection, which will attract the Chinese government likely.

3.3.2. Grim energy security situation

The oil consumption grows, oil imports increases year by year, and external dependency also raises with rapid economic development in China, 280 million tons of crude oil was imported in 2012, the external dependency reached 58%, which is a serious threat to China's energy security. EOR is one of the important means to ensure oil supply, and has become the preferred scheme on the implementation of CCS on a large scale due to production of crude oil increases. A lot of previous research on CO_2 flooding technology in China has obtained good effect, achieves large progress in drilling and completion technology; In turn, certain amounts of practical experience of the research and experiment on EOR contributed to CO_2 injection and monitoring. It can be expected with the development and application of CO_2 flooding technology, the development of CCS will make great progress [42].

On the other hand, compared with oil, the coal external dependency almost ranks zero even slightly export, although the consumption grows rapidly, making Coal to Liquid-CTL technology attracted much attention for a time in the context. CO_2 emissions relatively concentrated in the process of CTL (SHENHUA coal oil, for example, more than 70% of the emission concentration exceeds more than 90%). It is conducive to develop CO_2 capture and storage. Currently the only CCS whole process capture project is applying CTL as source of emissions in China. Therefore, CTL+CCS technical route has an important strategic position with the development of the CTL.

3.3.3. Growing international cooperation

As excellent performance on environmental protection, energy conservation and emissions reduction, high efficiency, low operating costs, effective regulation, China has become the object of developed countries compete to cooperation. According to IEA predicts, most part of new coal-fired power plants will be constructed focus on developing countries by 2050, the EU must will focus promotion on developing countries, in which China is preferred. While China also carry out extensive international cooperation actively, has carried out COACH, STRACO2 and Geo-Capacity, etc one after another. As for the further development of international cooperation and deepen, the technology gap with developed countries will be gradually shortened, technology risk and implement cost will be continuously reduced, so as to promote the development of CCS [43].

3.3.4. Supporting the development of renewable energy

The better situation of renewable energy development is a double-edged sword for CCS technology. On the one hand, CCS technology and renewable energy technology are two alternative technologies. In the case that renewable energy development can alleviate environmental pressure and reduce carbon emissions, the importance of CCS technology is bound to decline and detrimental to the development. However, considering the small proportion of renewable energy in the overall energy consumption structure currently, the impact is relatively less. With the increase in the proportion of renewable energy, the importance of CCS technology will be subject to greater impact. On the other hand, renewable energy promotes the CCS. CCS technology is questioned because of requiring additional energy consumption costs and waste of resources. While renewable energy is clean and can be used as an additional energy generation for CCS equipment, and CCS could reduce carbon emissions of fossil fuels at the same time, so the collocation of them can result in the maximum reduction carbon emissions with no increasing consumption of additional fossil energy. Thus, the resistance to CCS technology development can be reduced, and public acceptance is improved. Overall, renewable energy still has an active role for CCS technology in China, providing opportunity to develop CCS.

3.4. Challenges of CCS development in China

3.4.1. Imperfect policy and laws

Perfect government's policy and legal framework for large-scale CCS projects implementation do important means, long-term stable and clear energy policy will bring CCS technology users and investors confidence, increasing the investment return. CCS projects are often difficult to promote only relying on their own strength because of costly CCS implementation and high risk. Thus the benefits of numerous CCS large-scale implementation involved several aspects, including international organizations, national, local governments, businesses, and the social public [44–46]. It is significant to establish a legal and policy framework and effective running mechanism under the system which express and coordinate the demands of stakeholders. Despite the government supports a lot in China, several policy files and planning have been introduced; policy and legal framework focus on CCS still not comprehensive and perfect. The regulations under mandatory implementation need to ensure the implementation of CCS in China.

3.4.2. Low level of public acceptance

The social public acceptance of CCS directly determines the possibility of CCS on a large scale implementation in the future. The world's first carbon storage demonstration project a power company in Germany stared was forced to cancel just for local residents strongly opposition; An underground CO_2 storage the Shell company planned to establish in the Dutch in January 2010, caused 50,000 local people's strong resistance.

The public in China was investigated through the questionnaire form on the views about CCS and cognitive about CCS relevant legal system, the results show that the Chinese public for CCS development still has lots of doubts due to the lack of propaganda and information [44–46]. In addition, many environmental groups opposed to CCS, believes the essence is a transitional solution, taking EOR for example, the oil yielded accordingly increased the potential emissions of greenhouse gases, which not realized emissions fundamentally, either added excuse to expand continually for fossil energy industries.

3.5. Comprehensive analysis of CCS development technology in China

Development of CCS technology in China should seize the opportunity, continually to give full play to the advantages, improve the insufficient, and adopt the WO strategy (as shown in Table 10). Relying on the leading role of the government, regulations involved environment (pollution control and waste disposal), engineering construction, underground assignments, mining, oil and gas operation rules better to formulate to develop CCS projects. In terms of investment and financing, and technology transfer, domestic and foreign large enterprises joint together to launch financing funds, promoting the technology transfer and communication, with the utilization of international resources to promote CCS technology. The enterprises develop the CCS technology, relevant feasibility analysis and the implementation of the projects planning should be completed, within strong support from the government, speed up the development of CCS technology.

Overall, the SWOT analysis result shows that although there are technical obstacles and economic constraints, domestic energy consumption structure and huge storage potential have a positive role in promoting CCS, as well as sustainable and low-carbon energy development strategy in China. WO strategy listed in Table 8 should be undertaken, that includes the methods of increasing national economic support and research investment in key technologies. Besides, the feasibility and important role of the CCS projects should be publicized for wider public recognition and support. Specific suggestions in relation to the several points raised by WO strategy will be given in Section 4, in order to exert the development advantages of CCS in China, overcome the disadvantage, turn challenges into opportunities, and finally promote the rapid development of CCS technology in China.

4. Suggestions for CCS development in China

Based on research in Sections 3 and 4, as well as WO strategy points mentioned, specific implement countermeasures and suggestions are provided in various aspects of policy, capital, technology and public awareness, in order to reduce cost and promote efficient investment, perfect laws and regulations related to CCS, make security guarantee from policy and institution. Thus, a favorable external environment should be created for CCS which will promote CCS development orderly in China [47].

4.1. Introducing subsidies

Enterprises will hardly active to CCS to cut CO_2 emissions in the absence of carbon tax pressure, due to CCS cost is higher. Therefore, on one hand, classification rate or low rate of corporate tax are imposed on enterprises of CO_2 emissions by the government, to make enterprises take more consideration of environmental impact in the process of development in the future, and use CCS to cut emissions actively. On the other hand, the government implements the decarburization subsidy electricity price, or provides for subsidies for purchase of CCS related equipments and technology. With subsidies and support, CCS technology will be greatly promoted, though the CCS fixed investment is huge. In power plants, for example, the construction investment and operation cost are heavy, and the technology is not yet mature, the CCS development in enterprises will increase investment risk of CCS demonstration projects construction; while the high investment of the construction of CCS projects also cause the power plant higher generation cost, eventually lead to electricity price lack of market competitiveness. Therefore, financial subsidies need to achieve the orderly development of CCS of the electric power industry.

4.2. Promoting effective investment

The funds incentive policy of China should be treated separately in two different conditions facing of huge funding gap of CCS implementing:

(1) Demonstration, research and development stage. CCS is still in the period of research and development and small-scale demonstration, the possibility of economic interests is little, the main purpose is to increase the technology feasibility and development experience of CCS projects. The carbon capture demonstration projects and oil field injection experiment carried out presently in China are funded by enterprises from fundraising and national science and technology plan, supplemented by international cooperation projects funding, thus is still the public funds fundamentally as a result of the main project implementation body belonging to state-owned holding enterprises. So far, the realistic funding sources of research and development experimental include: government direct investment, government subsidies, public fund, tax cuts, large enterprises investment directly and public–private partnerships.
(2) Promotion stage. Huge varieties of funds should be attracted once entering into the popularization stage. Measures are: A certain proportion of electricity power plant generated are regulated from clean energy; Power supply without CCS use are limited; Implementing different feed-in tariff for different CO_2 emissions intensity of power plants; Developing CCS through the role of CDM mechanisms in developing countries, and raising money for CCS projects by the government through the auction of carbon credits or increasing the carbon tax [48].

4.3. Enhancing technology

Part aspect of CCS technology on a global scale has been mature at present, but basically still in the development and demonstration phase in China, such as EOR. Early in the implementation of CCS, the introduction of technology and equipment will speed up the development of CCS in China to some extent; in the long run, however, the problem of investment difficult is hard to solve by simple introduce. To really promote the development of CCS on a large scale, become the technology enterprise willing to adopt for emissions, CCS should be paid great attention to the research and development. CCS projects require lots of technology and capital investment, relying on the related research institutions and large state-owned enterprises, based on the research and demonstration projects, China now can conquer the researches on CO_2 capture, transportation and storage and other key techniques, implementing independent intellectual property rights, to reserve technology for possible large-scale application of CCS in the future.

Table 10
SWOT analysis of CCS development in China.

Exterior factors	Internal capabilities	
	Strength	Weakness
	• Great government Support • Coal-dominated energy structure • Huge geologic storage potential	• Poor economic feasibility • Lack of capital source • Immature technology
Opportunities • Increasing environmental pressure • Grim energy security situation • Growing international cooperation	SO Demands for energy, security, and environmental protection are urgent, relying on the government, implementing CCS activities extensive	WO CCS projects are affected by economic and technological factors, national financial support and industrial development of new technologies should be increased, achieving broader public support
Threats • Imperfect policy and laws • Low level of public acceptance	ST The government-led Is the key, targeted laws and regulations and outreach activities of CCS implementation projects need propaganda in place	WT Financial support and the acceptance by the government and public of CCS technology are required, in order to gain policy support

In addition, geological prospecting is necessary to actively carry out. With oil and gas fields and sedimentary basins as the pilot, enterprises of CCS implementation projects carry out geological survey from the storage capacity, injection, sealing, etc. and CO_2 storage potential and safety pre-assessment, for the clear, quantifiable storage site selection criteria that final introduced to prepare first-hand information [49].

4.4. Improving policy and regulation system

Preliminary, the law risk of CCS projects in China mainly refers to four aspects.

- Problems of application and approval, environmental impact assessment, technical uniform of CCS projects;
- Administration problem of oceanic sequestration, the nature and ownership issues of CO_2 stored, safety responsibility, environment and responsibility defined of climate damage;
- Information public, intellectual property protection of technical aspects, taxation;
- Uncertainty of international negotiations on climate change, etc.

Overall, the development direction of relevant CCS laws and mechanisms domestic are suggested following: (1) Tracking the legal status in relevant international laws of CCS closely, promoting CCS technology involved in the CDM or other similar incentive mechanisms; (2) Reference to the legislation in advanced countries, gradually establishing the applicable national laws and regulations and standard system as the infrastructure to implement CO_2 storage projects commercial; (3) With guidance of specification and reward mechanism proved successful of demonstration projects in advanced countries, actively encouraging the development of CCS. (4) Speeding up the research of supporting policies, namely, focusing on the special regulations and incentive policies, studying special procedures as application and approval, environmental impact assessment, conditions of site closed, accident emergency treatment, etc, designing incentive measures such as CCS drawback subsidies, CCS commercial insurance and CCS trust funds, to promote implementation of CCS on possible large-scale.

4.5. Strengthening CCS feasibility analysis

Compared to the relatively mature capture and transportation technology presently, the reliability of carbon storage technology remains to be seen internationally. The reliability of the technology needs to be further analysis before a wide range of applications, as well as the potential risk factors. Primary estimation of storage potential in China on the gas field, CO_2-EOR, deep saline aquifers, the exploitation of coal seam has been made, while a huge difference in accuracy between “actual storage” and the “matching” of the final implementation needed. Suggestions are proposed that conducted or led by the Ministry of Land and Resources, a nationwide inventory for geologic sequestration potential in China should be carried out, and corresponding storage safety standards are formulated, to make a grading or sorting on the storage sites in accordance with indicators like storage potential, storage safety and distances from large emission sources. Providing enough information for CCS investment and development in the future for enterprises, to reduce the risk of investors and builders, enhance the reliability of CCS implementation.

5. Conclusions

Jointly promoting the greenhouse gas emissions has become a global consensus in recent years. As one of the countries of economy growing fastest in the world and great CO_2 emissions, China faces dual pressure of the required obligation of emission reduction globally and sustainable development domestic, as the grim situation of emission reduction. Based on the coal-based primary energy structure and coal-dominated secondary energy structure, CCS is considered to be the most effective means to reduce emissions. Therefore, to realize the large-scale development of CCS in China, the development situation, challenges, disadvantages, advantages and opportunities of CCS are analyzed combined with the actual situation of China in the paper, and

recommendations are proposed with government forces, China should formulate corresponding policies, implement government subsidies, promote effective investment; encourage the electric power enterprises develop advanced CCS technology, strengthen the safety and feasibility analysis on the implementation of CCS. The factor of government, economic, social and natural affecting CO_2 capture, transportation and storage are considered on the basis of existing research in the paper, and innovative implementation suggestions based on the specific situation of CCS are proposed, providing a reference for the implementation of CCS projects in China. The extensive development of CCS, however, is a long lasting process, are influenced by unpredictable additional factors yet not predicted, which is also the direction of further research of the paper.

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References

[1] Ministry of Science and Technology, National Development and Reform Commission, Ministry of Foreign Affairs. Science and Technology special action to climate change in China . Beijing; 2007. 11.
[2] Vatalis K I, Laaksonen A, Charalampides G, et al. Intermediate technologies towards low-carbon economy. The Greek zeolite CCS outlook into the EU commitments. Renewable Sustainable Energy Rev 2012;16(5):3391–400.
[3] Xiaoli Liu, Kun Zhang, Ming Zeng. Impact assessment of carbon price on relatively competitive of low carbon base load generation technology. Water Resour Power 2013;31(4):226–44.
[4] 〈http://www.ce.cn/xwzx/gnsz/gdxw/201101/22/t20110122_22162727.shtml〉.
[5] 〈http://news.bjx.com.cn/html/20120810/379617.shtml〉.
[6] Karakosta C, Pappas C, Marinakis V, et al. Renewable energy and nuclear power towards sustainable development: Characteristics and prospects. Renewable Sustainable Energy Rev 2013;22:187–97.
[7] Hamawand I, Yusaf T, Hamawand S. Coal seam gas and associated water, a review paper. Renewable Sustainable Energy Rev 2013;22:550–60.
[8] Van Bergen F, Gale J, Damen K J, et al. Worldwide selection of early opportunities for CO_2 enhanced oil recovery and CO_2 enhanced coal bed methane production. Energy 2004;29(9):1611–21.
[9] National Development and Reform Commission (NDRC). Notice on promoting carbon capture, utilization and storage experiment and demonstration; April, 2013.
[10] 〈http://wenku.baidu.com/view/ba6f76d2195f312b3169a57d.html〉.
[11] Pires J C M, Martins F G, Alvim-Ferraz M C M, et al. Recent developments on carbon capture and storage: an overview. Chem Eng Res Des 2011;89(9):1446–60.
[12] China National People's Congress(NPC). Environmental Protection Law Amendment (Draft); August, 2012.
[13] 〈http://news.xinhuanet.com/video/2007-06/05/content_6198211.htm〉.
[14] Environmental Protection Administration(EPA). Interim measures for public participation in environmental impact assessment; February, 2012.
[15] 〈http://www.gov.cn/zwgk/2009-08/21/content_1398541.htm〉.
[16] China National People's Congress(NPC). Energy Conservation Law of the People's Republic of China; October, 2007.
[17] Radgen P, Kutter S, Kruhl J. The legal and political framework for CCS and its implications for a European Utility. Energy Procedia 2009;1(1):4601–8.
[18] Dixon T, Leamon G, Zakkour P, et al. CCS projects as Kyoto protocol CDM activities. Energy Procedia 2013;37:7596–604.
[19] Cormos CC. Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS). Energy 2012;42(1):434–45.
[20] Gibbins J, Chalmers H. Carbon capture and storage. Energy Policy 2008;36(12):4317–22.
[21] Xinchun LI, Yongbin Sun. Status and prospects of CO_2 capture. Electr Power Technol 2010;22(4):21–6.
[22] Chen Qixin Ji Zhen. Kang Chongqing, et al. Carbon Analysis of different operation modes of carbon capture plants. Power Syst 2012;36(18):109–15.
[23] Kanniche M, Gros-Bonnivard R, Jaud P, et al. Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture. Appl Therm Eng 2010;30(1):53–62.
[24] Carbon dioxide capture and storage. Cambridge University Press; 2005; 16–27.
[25] Koornneef J, van Breevoort P, Hamelinck C, et al. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. Int J Greenhouse Gas Control 2012;11:117–32.
[26] ZareNezhad B, Hosseinpour N. An extractive distillation technique for producing CO_2 enriched injection gas in enhanced oil recovery (EOR) fields. Energy Convers. Manage. 2009;50(6):1491–6.
[27] Working Group III of the Intergovernmental Panel on Climate Change. IPCC special report on carbon dioxide capture and storage. Cambridge: Cambridge University Press; 2005.
[28] Heddle G, Herzog H, Klett. M. The economics of CO_2 storage. MA: Massachusetts Institute of Technology; 2003.
[29] Xiaochun Li, Zhiming Fang, Ning Wei, et al. Technology roadmap study on CO_2 capture and storage. Rock Soil Mech 2009;30(9):2674–8.
[30] 〈http://ccs.ditan360.com/InfoNews-18.html〉.
[31] 〈http://www.chng.com.cn/n31537/n221635/n221638/c492623/content.html〉.
[32] 〈http://news.sohu.com/20091029/n267837409.shtml〉.
[33] Yang J, Chen B. Integrated evaluation of embodied energy, greenhouse gas emission and economic performance of a typical wind farm in China. Renewable Sustainable Energy Rev 2013;27:559–68.
[34] The State Council. China's response to climate change policy and action; October, 2008.
[35] 〈http://www.askci.com/news/201309/24/2417149107087.shtml〉.
[36] 〈http://www.pnl.gov/〉.
[37] Yanfeng Liu, Xiaochun Li, bing Bai. Preliminary evaluation of coal seam capacity of CO_2 storage in China. Chin J Rock Mech Eng 2005;24(16):2947–52.
[38] Koo J, Han K, Yoon ES. Integration of CCS, emissions trading and volatilities of fuel prices into sustainable energy planning, and its robust optimization. Renewable Sustainable Energy Rev 2011;15(1):665–72.
[39] The future of coal: options for a carbon-constrained world. MA, USA: MIT; 2007.
[40] Hammond G P, Akwe S S, Williams S. Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. Energy 2011;36(2):975–84.
[41] Ma H, Oxley L, Gibson J, et al. A survey of China's renewable energy economy. Renewable Sustainable Energy Rev 2010;14(1):438–45.
[42] Lo K. A critical review of China's rapidly developing renewable energy and energy efficiency policies. Renewable Sustainable Energy Rev 2014;29:508–16.
[43] Yuan J H, Lyon TP. Promoting global CCS RDD&D by stronger US–China collaboration. Renewable Sustainable Energy Rev 2012;16(9):6746–69.
[44] Nykvist B. Ten times more difficult: quantifying the carbon capture and storage challenge. Energy Policy 2013;55:683–9.
[45] Hansson A, Bryngelsson M. Expert opinions on carbon dioxide capture and storage—a framing of uncertainties and possibilities. Energy Policy 2009;37(6):2273–82.
[46] Bowen F. Carbon capture and storage as a corporate technology strategy challenge. Energy Policy 2011;39(5):2256–64.
[47] Rai V, Victor D G, Thurber MC. Carbon capture and storage at scale: lessons from the growth of analogous energy technologies. Energy Policy 2010;38(8):4089–98.
[48] Scott V. What can we expect from Europe's carbon capture and storage demonstrations?. Energy Policy, 2012.
[49] Stephens J C, Jiusto S. Assessing innovation in emerging energy technologies: socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA. Energy Policy 2010;38(4):2020–31.